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Dear Harin,

This is the second quarterly report for Phase II of EPV's cost-shared subcontract ZXL-5-44205-05 "Uniform, High Efficiency, Hybrid CIGS Processing with Application to Novel Device Structures" awarded under the Thin Film Photovoltaics Partnership Program. The nominal period covered by the report is 06/18/06 – 09/17/06.

The following sections summarize some of our activities in this quarter and report some relevant news items:

1) Small area devices in R&D system Hercules;
2) Large area modules in Zeus;
3) Surface treatment after CIGS deposition;
4) Relevant news items.

1) Small area devices in R&D system Hercules

We have investigated the effects of changing the substrate temperature (T_s) for CIGS deposition on cell performance. The baseline T_s was set at 535°C. Lowering T_s could benefit large area module fabrication by avoiding substrate warping. The experiments were performed using the simplified hybrid process in the small area Hercules system where the depositions were done at constant temperature as well as steadily decreasing temperature during film growth. Our intention was to see the dependency of cell performance on varying degrees of elemental diffusion when growth temperature was reduced. Table I below summarizes device performance for CIGS thin films grown at three different temperature settings.

Table I. Device performance at different deposition temperatures

Run	T_s (^oC)	Thickness (μm)	Ga/(In+Ga)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Eff (%)
H062806	535	1.2	0.35	585	29.2	66.6	11.4
H070306	495	1.26	0.34	593	30.8	65.3	11.9
H070606	495	1.21	0.33	578	30.8	71.2	12.7
H072706	495	1.4	0.31	575	31.3	65.8	11.8
H072806	495/475*	1.45	0.31	583	32.7	63.7	12.1
H082106	495/475*	1.41	0.32	592	32.8	65.6	12.7
H083106	495/475*	1.52	0.26	557	34.1	62.7	11.9

* T_s was gradually decreased from 495°C to 475°C during CIGS deposition.

The efficiency data shown in Table I suggest that decreasing T_s from the standard value of 535°C can slightly increase the efficiency of the device. However, an increased CIGS thickness was targeted in the 495/475°C runs, resulting in a higher current density (and apparently lower fill factor). Once this factor is recognized, it would appear that a temperature of 495°C is optimal, at least from this set of experiments.

In all of the above samples, the Ga content lies between 0.31% - 0.35% except for the last run. It is evident that upon decreasing Ga content from 0.32 to 0.26, J_{sc} is increased by 4%, where as V_{oc} and efficiency are decreased by 6% and 6.3% respectively. So an optimum amount of Ga needs to be doped into the absorber layer to get maximum device efficiency. We are in the process of installing a Ga regulator in the Hercules system to more accurately control Ga content in CIGS. This will enable us to get accurate information about effects of varying T_s on device performance at a fixed Ga/In ratio.

2) Large area CIGS modules

Efforts were made to produce a more efficient module, closer to the device performance from the Hercules system, using the simplified hybrid process in the large area Zeus system. Table II summarizes the performance of some of the large area modules having different segment numbers.

Table II. Performance of large area modules

ID	Segment #	V_{oc} (V)	V_{oc}/cell (mV)	I_{sc} * (A)	J_{sc} (mA/cm^2)	Ap. area (cm^2)	FF %	Power (W)	Efficiency (%)
Z1807	47	24.81	528	1.185	23.88	2332	53.96	15.86	6.8
Z1811	62	35.70	576	0.51	20.99	1499	56.21	10.18	6.8
Z1818	55	27.15	494	1.23	24.97	2710	49.49	16.53	6.1
Z1819	61	30.52	500	1.18	24.55	2934	50.58	18.22	6.2
Z1820	50	23.34	466	1.13	22.62	2497	51.99	13.71	5.5

* outdoor measurements normalized to one sun

The degraded performance of the module compared to the small area cell can be described by the following factors:

- Non-homogeneity -
  There is difficulty in depositing a CIGS absorber film of uniform composition and quality on large area modules.

- Dimensional changes of the substrate -
  The dimension of the soda lime glass substrate changes during processing due to high temperature CIGS growth. This causes misalignment of P1 and P2 scribes during monolithic integration of the module. As a result, the dead area is larger than expected. We have recently built a long-base micrometer caliper to measure such dimensional changes in the module. Hence it should be possible to minimize inactive current generation areas in the coming days.

- Power loss -
  There are power losses due to sheet resistance of the ZnO:Al and also due to ZnO-Mo contact resistance. We are currently focusing on reducing the ZnO-Mo contact resistance while keeping the sheet resistance to a minimum.

3) Surface treatment after CIGS deposition

CIGS material used in photovoltaics is prepared at high temperatures to achieve the composition $Cu(In_{0.7}Ga_{0.3})Se_2$. The required preparative techniques and feedstock quality impart several undesired impurities in the material phase which is quite rough at the surface. The unwanted impurities could consist of binary constituent phases, oxides of component elements, sodium compounds and several traces of carbon compounds (see C.L. Perkins et al., Proc. 31St IEEE PVSC, Lake Buena, FL, 2005, 255). Several research groups have reported work regarding improvement of the thin-film CIGS surface to enhance device efficiency. Unfortunately such works are often non-reproducible (see T. Nakada et al., Solar Energy and Solar Cells, 1997, 49, 285) when attempted at different research laboratories.

At EPV we have been experimenting with two surface treatment techniques and we have achieved reproducible results with hundreds of CIGS test devices with related improvements in device parameters. Device test results achieved using these surface treatments are being reported herein. In Table III, device results from a freshly prepared 17” x 38” CIGS plate Z1817 are reported. The plate was prepared on 8/7/2006 and six 2” x 6” test samples were cut from it on 8/9/2006. Surface treatment-1 was applied before the standard CdS deposition process. Average device parameters V_{oc}, FF, and efficiency etc. were measured.

Table III. Average device parameters from six test CIGS samples cut from freshly-prepared Zeus plate Z1817

CIGS treated 8/9/2006	CIGS deposited 8/7/2006				
Sample#	Pretreatment	V_{oc} (mV)	FF (%)	J_{sc} (mA/cm^2)	Eff (%)
Z1817-1 B2	Treatment -1	539.2	59.24	29.91	9.55
Z1817-1 A2	Treatment -1	534.4	58.64	30.11	9.44
Z1817-2 B2	Treatment -1	535.6	60.71	29.78	9.68
Z1817-2 B3	Treatment -1	523.5	60.61	29.54	9.37
Z1817-3 A2	Treatment -1	513.2	55.32	29.35	8.33
Z1817-3 B1	Treatment -1	518.4	58.48	29.47	8.93
Z1817-4 B2	Treatment -1	547.4	57.64	29.6	9.34
Z1817-4 B1	Treatment -1	546.8	57.02	29.55	9.21
Z1817-5 B1	Treatment -1	532.3	59.37	30.13	9.52
Z1817-5 A1	Treatment -1	529.5	57.81	30.28	9.27
Z1817-6 B1	Treatment -1	509.4	57.28	29.14	8.50
Z1817-6 B2	Treatment -1	502.8	56.32	28.57	8.09
AVERAGE		527.7	58.20	29.62	9.10

The plate Z1817 was left in ambient lab atmosphere for about three weeks. The performance of the CIGS was tested by cutting test samples from it. The comparative test device results using treatment-1 and treatment-2 are reported in Table IV.

Table IV. Device test results from CIGS plate Z1817 after allowing it to stand in room air for 3 weeks.

treated 9/1/2006	**CIGS deposited 8/7/2006**				
Sample#	**Pretreatment**	**V_{oc} (mV)**	**FF (%)**	**J_{sc} (mA/cm^2)**	**Eff (%)**
Z1817-46	None	534.8	45.05	29.91	7.21
Z1817-56	None	514.3	51.38	29.68	7.84
AVERAGE		**524.55**	**48.22**	**29.80**	**7.52**
Z1817-41	Treatment -1	570	55.69	28.91	9.18
Z1817-44	Treatment -1	575	47.71	29.83	8.18
Z1817-48	Treatment -1	535.2	52.59	30.57	8.60
Z1817-51	Treatment -1	564.2	50.87	28.94	8.31
Z1817-54	Treatment -1	553.6	49.84	29.85	8.24
Z1817-58	Treatment -1	542.2	53.42	30.73	8.90
AVERAGE		**556.70**	**51.69**	**29.81**	**8.57**
Z1817-42	Treatment 2	560.3	61.34	30.83	10.6
Z1817-45	Treatment- 2	571.7	60.32	31.17	10.7
Z1817-49	Treatment- 2	537.4	60.85	31.49	10.3
Z1817-52	Treatment -2	552.4	58.89	30.9	10.1
Z1817-55	Treatment- 2	548.9	61.91	30.23	10.3
Z1817-59	Treatment- 2	523.9	59.19	30.57	9.5
AVERAGE		**549.10**	**60.42**	**30.87**	**10.24**

These tests showed that CIGS plate Z1817 still retained photovoltaic properties, and the untreated cells showed an average efficiency of 7.52% (Table IV). Even after standing in room air, with treatment-1 the V_{oc} of test devices had an average value of 556.7 mV vs the average V_{oc} of 527.7mV of the freshly prepared devices as reported in Table III. However, the average test cell efficiency had decreased to 8.57% from the original value of 9.10%.

Next we applied treatment-2 to the test cells from plate Z1817. The device parameters (Table IV) showed significant improvement in comparison with the test results from treatment-I using freshly-prepared as well as aged Z1817 samples (Table III, and Table IV). The treatment-2 is obviously more effective in overall cell efficiency improvement. An average device efficiency of 10.24 % was achieved with significant enhancement in cell current and FF (Table IV).

We had previously tested the effectiveness of treatment-2 in improving the photovoltaic material qualities by applying this treatment to test cells of a 10-month-old plate Z1751. This plate was prepared and tested on 1/27/2005. For completeness, original test results and results after treatment-2 are listed in Table V.

Table V. The comparison of surface treatment-1 using freshly prepared CIGS with surface treatment-2 using 10 month old CIGS.

CIGS treated 1/27/2005	**CIGS deposited 1/27/05**				
Sample#	**Pretreatment**	**V_{oc} (mV)**	**FF (%)**	**J_{sc} (mA/cm^2)**	**Eff (%)**
1751-1	Treatment -1	454.7	64.89	23.31	6.88
1751-2	Treatment -1	574.9	67.24	27.83	10.76
1751-3	Treatment -1	594.3	67.71	25.18	10.13
1751-4	Treatment -1	526	65.08	24.06	8.24
AVERAGE		**537.5**	**66.2**	**25.1**	**9.0**
CIGS treated 11/14/2005	**CIGS deposited 1/27/05**				
Z1751-21	Treatment- 2	623	59	27.16	9.98
Z1751-23	Treatment- 2	619.8	60.86	27.6	10.41
Z1751-25	Treatment- 2	617.2	61.94	25.81	9.87
Z1751-27	Treatment- 2	615.8	67.51	26.5	11.02
AVERAGE		**619.0**	**62.3**	**26.8**	**10.3**

After treatment-2, the test devices showed significant improvements in V_{oc} and current with clear enhancement in related device efficiency. We are trying to understand how the chemical treatment-2 could be effective in improving the CIGS surface qualities. We are continuing our work comparing treatment-1 with treatment-2 using freshly prepared CIGS test samples from our Hercules deposition chamber.

4) Some Corporate news items

- Dr. A.E. Delahoy participated in the 1st International Symposium on Transparent Conductive Oxides, 23-25 October 2006, Hersonissos, Crete, and gave an oral presentation entitled “High Performance TCOs Prepared by Reactive-Environment, Hollow Cathode Sputtering”.
- Production of tandem junction amorphous silicon modules at EPV’s Lawrenceville facility is now a three-shift operation and additional equipment is being installed to expand capacity. Substrate size, currently 25” x 49”, will be increased to 28” x 52”. EPV plans to build a larger manufacturing plant at its new 65,000 ft^2 facility in Hamilton, NJ. The Lawrenceville facility will be retained.
- EPV is shipping equipment for an IMS (Integrated Manufacturing Facility) to its JV partner Solar+ in Portugal, and has recently signed contracts to supply IMSs in Spain and Taiwan.

Sincerely,

Alan E. Delahoy
Principal Investigator

Baosheng Sang
Scientist